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US Army Research Laboratory

Summary and Findings of the ARL Dynamic Failure Forum

by Brady B Aydelotte, Christopher S Meyer, and
Asher A Rubinstein

NOTICES

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14. ABSTRACT

The US Army Research Laboratory (ARL) Dynamic Failure Forum was organized as a 2-day forum focused on assessing the state of the art in experimental, theoretical, and computational studies of dynamic failure. The forum also focused on identifying technologies and approaches that will yield improvements in researchers' ability to understand and model dynamic failure. The discussion revolved around 2 common scenarios where dynamic failure is important: dynamic penetration and explosive/blast induced fracture. This report is a summary of the findings and recommendations of the attendees of the ARL Dynamic Failure Forum, which occurred March 28 and 29, 2016. The most consistent recommendations that emerged were that material model and analysis code development must be a long-term priority for the Army with enduring, appropriate levels of support directed toward Army-specific problems. Experimental exploration of material behavior and an improved ability to parameterize material models is essential to improving modeling of important Army problems.

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1. Summary

The importance to US Army research of understanding the dynamic failure of materials due to explosive loading and projectile penetration lead to the organization of a forum in which subject matter experts from across Army laboratories, with collaborators and code developers from Department Of Energy (DOE) laboratories, Defence Science and Technology Laboratory (DSTL) in the United Kingdom, and Defence Science and Technology Organisation (DSTO) in Australia gathered to assess the state of the art of modeling and simulation (M&S) of dynamic failure and experimental observation of dynamic failure, identify areas where improvement is needed to the state of the art, and begin to establish a path toward such improvement by identifying deficiencies in and suggest ways of improving the understanding of dynamic failure of materials. This forum was also hosted with the goal of identifying new directions and new ideas for basic research both within the Army research, development, and engineering laboratories and the academic community.

The forum began with 2 keynote presentations, which highlighted the current state of the art in M&S and experimental observation of dynamic failure respectively, and suggested possible future directions for computational and experimental research into dynamic failure of materials. A discussion panel format facilitated open and collaborative conversations addressing key issues. Panel discussions are summarized in Section 5 of this report.

Major findings include the following: There must be a serious institutional commitment to generating sufficient experimental data to parameterize existing and new material models, and to developing and maintaining material models within DOE codes that are of interest to the Army. Army institutions must incentivize vital efforts such as materials characterization, which is essential to accurate computational modeling, must improve funding to DOE code development teams for support functions, and must support code development that relates to core Army mission space and priorities. Additionally, Army institutions should incentivize collaboration between Army and DOE laboratories represented at this forum, as well as among the larger US Department of Defense (DOD) laboratory and academic community.

Following from these major institutional-level discussion points came many bench-level science and engineering discussion points, which are summarized here. Material models should be maintained, documented, and developed for portability, and analysis software must facilitate integration of new material models. Material models require improvements in thermal properties and behaviors, simultaneous

operation of material deformation and failure criteria, inclusion of stochastic material property variability in damage models, and improvement in material properties and mechanisms across multiple-length scales. Experiments, particularly material characterization and ballistic experiments, require more statistical replication to provide insight into material variability, require multidiagnostic experiments, and require experimental emphasis on exploring initiation of failure events. It is necessary to quantify uncertainty in model predictions arising from mathematical formulation as well as due to uncertainty in model inputs. Finally, there must be increased collaboration between modelers and experimentalists.

A survey of attendees was conducted and the following summarizes the survey findings. Attendee responses identified 11 areas where focus is required to improve the state of the art of understanding dynamic failure events, which are listed here in order of importance: constitutive model development and support; constitutive model parameterization; experimental development in support of material behavior exploration; collaboration; experimental development in support of parameterization; code improvements; multiscale modeling; uncertainty quantification; organizational support; challenge problem; and modeling post processing tools.

The most consistent recommendations to emerge from the discussions and surveys generated by this forum are that material model and analysis code development must be a long-term priority for the Army with enduring, appropriate levels of support directed toward Army-specific problems. Experimental exploration of material behavior and an improved ability to develop and parameterize material models is essential to improving modeling of important Army problems, which will facilitate enhanced lethality and protection for Army Soldiers.

2. Introduction

Material failure is an extremely common problem. Dynamic failure, which is rapid failure due to rapid insults, ranges from trivial irritations such as rock chips in windshields to serious and even fatal events such as car crashes and bomb blasts. Understanding dynamic failure is the essential key to preventing or coping with it.

The US Army has a uniquely significant need to understand dynamic failure due to both explosive loading and projectile impact. As the primary land combat force of the United States of America, these types of scenarios are commonly encountered by the US Army. Therefore the US Army must be able to experimentally explore and numerically model dynamic failure events. As threats to the US Army proliferate, the size of the parameter space for armor and weapon design grow rapidly, with corresponding cost increases. This suggests that the value of numerical modeling tools in the design process will also grow if sufficient confidence exists in those tools.

Important ballistic experiments, such as arena tests to quantify fragmentation behavior in munitions and limit velocity experiments for body armor, are fielded with minimal diagnostics and as such provide little or no insight into material behavior. This has continued in spite of significant improvements in experimental techniques that have taken place at US Government laboratories, academia, and industry. These techniques include the development of the velocity interferometry system for any reflector (VISAR) (Barker and Hollenbach 1972), photon Doppler velocimetry (PDV) (Strand et al. 2006), digital image correlation (DIC) for use in mechanics research (Chu et al. 1985), proton radiography with magnetic lenses (King et al. 1999), X-ray phase contrast imaging (Luo et al. 2012), and the ongoing evolution in high-speed camera technology. However, ever increasing costs of experimental data acquisition means that accurate and reliable numerical modeling becomes particularly important to assist in the process of evaluating options and developing optimal solutions for protecting Soldiers and helping them achieve their missions.

Unfortunately, as important as understanding dynamic failure is to the Army, progress in adopting improved numerical tools and experimental capabilities into widespread use is slow. New and more sophisticated material models are routinely developed by researchers in academia, in the DOE, and in the DOD, yet many of the material models commonly available to Army engineers for dynamic analysis at the continuum scale have changed little in the past 10 or even 20 years.

The need for improved simulation capabilities becomes even clearer when the scale of the modeling that takes place is considered. Table 1 shows the total number of core hours available across the unclassified portion of the Department of Defense High Performance Computer Modernization Program. Not taking into account maintenance periods, there are over 7 billion core hours available each year across 15 systems of various sizes. The systems are upgraded or replaced every 3 to 5 years with larger, more powerful machines. This represents an enormous capital investment in modeling and simulation resources to aid the DOD and its subsidiary organizations in developing new capabilities for American Soldiers, Sailors, Marines, and Airmen.

Table 1 Yearly core hours per unclassified high-performance computer (HPC) system. Core numbers were taken from the DOD HPC website (DOD HPC Centers 2016).

DOD HPC system	Cores	Total hours
Armstrong	29160	255,441,600
Conrad	48736	426,927,360
Copper	14720	128,947,200
Excalibur	99136	868,431,360
Garnet	150912	1,321,989,120
Gordon	48736	426,927,360
Haise	19520	170,995,200
Kilrain	19520	170,995,200
Lightning	56880	498,268,800
Predator	1004	8,795,040
Riptide	12096	105,960,960
Shepard	28632	250,816,320
Spirit	73440	643,334,400
Thunder	115776	1,014,197,760
Topaz	124416	1,089,884,160
Total		**7,381,911,840**

The top 6 continuum scale finite element/finite volume analysis codes by total projected hours on DOD High Performance Computing Modernization Program (HPCMP) computers for all codes and applications are listed in Table 2. Of these, CTH (McGlaun and Thompson 1990), an Eulerian large deformation and shock wave mechanics hydrocode developed by Sandia National Laboratories, was the largest consumer of hours. The number of projected use hours for these codes represents a significant fraction of the total available computational power for the DOD.

Table 2 The top 6 finite element or finite volume codes for modeling continuum scale dynamic events (Vanden 2015)

Code
CTH
ALEGRA
ALE3D
ABAQUS
EPIC
LS-DYNA

The ability to model material failure and fracture on the continuum scale has not grown much beyond the early continuum damage models in these codes. It is difficult to quantify the usage of different material and failure models because that data is not collected on the DOD HPCMP platforms. However, based on the authors' own experience, the most widely used continuum damage model is the Johnson-Cook damage model (Johnson and Cook 1985). Originally introduced to the computational modeling community in a 1985 publication, the Johnson-Cook damage model (Johnson and Cook 1985), along with the Johnson-Cook metal plasticity model (Johnson and Cook 1983), were first included in Johnson's Lagrangian finite element code, EPIC (Johnson 1978), and by the late 1980s in other analysis codes including the Eulerian finite volume code CTH. These models were extremely well received; they are simple and robust and produce adequate results in many situations. They were also parameterized for a wide variety of materials. This last point is significant and is addressed in detail later on.

That the Johnson-Cook and other legacy continuum damage "work horse" models continue to be popular despite advances in computer technology and power, which facilitate more complex models, is a testament to their utility. However, this is also indicative of a variety of factors that prevent newer technologies and models from making their way into common finite element/finite volume analysis codes. This theme was explored at the US Army Research Laboratory (ARL) Dynamic Failure Forum and is addressed later in this report.

Modeling and simulation are most useful when carefully coupled with experimental observations. Experimental observations provide the ability to validate simulation results as well as parameterize material models. Significant development or improvement in experimental techniques uniquely suited for the study of dynamic events has taken place in the last 40 years. These techniques, mentioned above, include VISAR (Barker and Hollenbach 1972), PDV (Strand et al. 2006), and other techniques. There have also been substantial improvements in characterization techniques like X-ray computed tomography and electron backscatter diffraction measurements. Unfortunately, obtaining sufficient and appropriate experimental data for modeling and validation is often a major bottleneck in the modeling process. Automated material characterization has developed in materials science (Spowart et al. 2003), but nothing comparable has had much impact in dynamic solid mechanics. Inverse methods to parameterize models such as brute force material model optimization or the Virtual Fields Method (Pierron and Grédiac 2012) are powerful techniques but have not yet found wide application in modeling dynamic failure.

We organized the ARL Dynamic Failure Forum in order to address some of these aforementioned issues and to begin to understand where the US Army's experimental studies and computational modeling of dynamic failure events need to grow and improve. The forum consisted of 2 days of panel discussions and meetings at ARL with invited luminaries with expertise in material characterization, explosive and blast loading, material model development, and numerical modeling technology with the objective of determining how the Army can improve its ability to understand and model dynamic failure processes.

3. ARL Dynamic Failure Forum Description

The ARL Dynamic Failure Forum took place at the ARL Conference Center at Aberdeen Proving Ground, Maryland, on March 28 and 29, 2016. The topics discussed at the forum focused on dynamic failure in fundamental Army problem spaces involving fragmentation and penetration. Key note talks were given by Dr George A Gazonas of ARL on the state of the art of computational modeling of dynamic fracture in solids and by Dr Michael B Zellner of ARL on the state of the art of experimental observation and characterization of dynamic failure.

Panel-style discussions were held in which a small panel of subject matter experts were selected to motivate and guide discussions by the at-large group. At-large discussions were divided into penetration on March 28th and blast or shock induced fragmentation on March 29th. On each day, at-large discussions of penetration and fragmentation were further divided into experimental and computational/theoretical segments, and within each segment material specific issues were addressed for ductile materials (metals), hard materials (ceramics, glasses, and geomaterials), and soft materials (polymers, composites, and biomaterials). Figure 1 illustrates the flow of the ARL Dynamic Failure Forum.

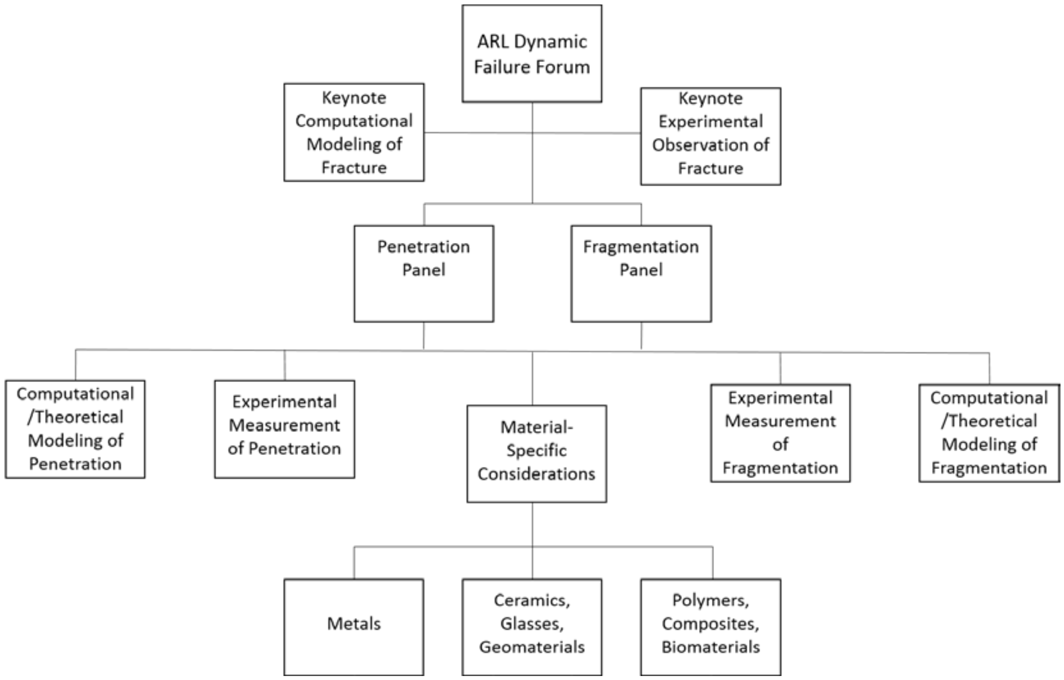

Fig. 1 The flow of topics for the ARL Dynamic Failure Forum held March 28 and 29, 2016

4. Attendees

More than 65 scientists and engineers attended the ARL Dynamic Failure Forum. Attendees came from 11 different research and engineering organizations in 3 different countries including the ARL; US Army Engineer Research and Development Center (ERDC); US Army Armament Research, Development and Engineering Center (ARDEC); US Army Aviation and Missile Research, Development and Engineering Center (AMRDEC); US Army Research Office (ARO); Sandia National Laboratory (SNL); Lawrence Livermore National Laboratory (LLNL); Los Alamos National Laboratory (LANL); the UK DSTL; the Australian DSTO; and the University of Alabama at Birmingham (UAB).

The significant number of attendees, and the different organizations represented, spanned a diverse but focused cross section of experimentalists, modelers, and code developers, who provided a rich variety of perspectives. A list of the attendees is included in Appendix A.

5. Results and Conclusions

The authors took notes and collected notes from volunteers to document the main discussion points. The authors also conducted a survey of the attendees on both days to capture their views on the events of the day. The panel discussion results and the summary of the surveys are reported below.

5.1 Summary of the Discussions and Views of the Attendees

The discussions and views of the attendees were diverse and interesting. However, some major themes emerged as follows:

- Material model and analysis code development must be a long-term institutional priority within the Army to improve its utility for Army-centric problems.
- Material model development should be pursued in a more holistic fashion where model development, transfer to Army-utilized software developers (e.g., DOE, commercial), and parameterization are all considered important parts of a model's life cycle and appropriate personal and institutional incentives are provided for supporting each of these functions.
    - Material models should be portable and code agnostic to the maximum extent possible.
    - Efficient transfer of technology from universities to the Army and from the Army to software developers should be a priority.
    - Computational and experimental tools for efficient material model parameterization require development and more support.
- Collaboration between model users, experimentalists, and developers must be strengthened within and across organizations.
- Material studies to understand mechanisms of material deformation and failure and characterization to parameterize models both require strong support, particularly for nonmetals such as polymers, biomaterials, composites, and ceramics. In some of these areas new or improved material characterization techniques are needed.
- Models and methods are needed to represent phenomena such as fracture and failure more accurately than the current capabilities of continuum damage models.

5.2 Panel Discussion Results

Summaries of panel discussions, main talking points, survey results, and general comments are presented in the following list. Interestingly, many of the same issues emerged repeatedly in different sessions, so the results are grouped into computational; experimental; material specific; and programmatic, organizational, and policy sections. The following are the main points of discussion and essential recommendations.

5.2.1 Computational and Theoretical Improvements Needed to Improve Army Modeling Capabilities

- Improved material models are important to improved modeling outcomes and results.
    - There must be increased collaboration between modelers and experimentalists. Models should be developed that use real experimental outputs and experimentalists should conduct experiments that yield useful model inputs where possible.
    - To improve material modeling, more effort must be placed on subgrid or subscale material properties and mechanisms. This effort will be related to both traditional models in which the subgrid behavior is captured by evolution equations and to explicit multiscale modeling efforts in which subgrid physics is captured explicitly in computational models that function at lower length scales.
    - There was some discussion about material model complexity. Some attendees felt that generally more complex models will be required to achieve more accurate results. Others argued that since no model will be a universal solution regardless of its complexity, simpler models will remain more useful, particularly if modelers can live with a certain degree of parameter tuning. One attendee suggested that perhaps we should focus efforts on parameterizing existing models for more materials rather than on new material models.
    - Multiscale modeling efforts may be able to provide guidance and insight, if not hard numbers, for new and improved continuum scale models.
    - Material models require better thermal properties and better understanding of thermal behavior.

- Improved material models that are better able to capture different deformation and failure criteria that operate simultaneously are essential. This may require improvements in code architecture and solver coupling so multiple failure and deformation mechanisms can operate simultaneously.
- Codes and models need to be able to capture crack-like behaviors such as stress concentrations and strong discontinuities across interfaces. Commonly used continuum damage models are not yet able to do this.
- In traditional damage models, the inclusion of stochastic material property variation, which is physically reasonable, slightly improves solution convergence with mesh refinement.
- Analysis software needs to facilitate easier integration of new material models. Material models need to be as portable as possible to facilitate ease of use with different simulation codes, comparison of different codes, and comparison of different models within codes.

5.2.2 Experimental Improvements Needed to Advance Army Material Characterization Capabilities

- Experiments, particularly material characterization and ballistic experiments, require more statistical replication to provide insight into material variability. More experimental detail should be reported to facilitate use of the data.
- Multi-diagnostic experiments provide more constraints on material properties and behavior and should be performed whenever possible.
- More experimental emphasis should be placed on exploring initiation and nucleation events for improved understanding of material behavior.

5.2.3 Material Specific Aspects of Experimental and Computational Exploration of Dynamic Failure

- Metals breakout meeting.
  - The properties of material models are an issue that requires improvement.
    - Where possible, models should use internal state variables that are measurable rendering connection to experimental data more straightforward.
    - Uncertainty in model predictions due to the mathematical formulation of a model is a challenge to quantify over and above

quantifying uncertainty in model predictions due to uncertainty in the individual model inputs.

  - Additional understanding of failure mechanisms is necessary, but obtaining that knowledge is challenging.
    - Multiscale modeling may provide insight into mechanisms and processes taking place at lower-length scales, in effect becoming numerical experiments for higher-length scales.
    - Arrested (i.e., stopped midexperiment and frozen in present state) experiments may allow some insight into failure mechanisms, but fielding and understanding such experiments has proven challenging. Further development is required.
  - Materials characterization remains important even in well studied materials like metals. More materials characterization across all rate, length, temperature, and strength regimes is needed.

- Ceramics and geomaterials breakout meeting.
  - Additional characterization of ceramics, especially at extreme states of pressure and temperature is important for accurate modeling. Obtaining these data remains a substantial challenge because of the high strength and brittle behavior of many ceramics.
    - The shear strength of ceramics under confinement remains poorly understood and difficult to diagnose experimentally. This deficiency is due to the high strength and large confinement pressures required to explore the constitutive behavior of these materials or approximate the conditions experienced during ballistic impacts. Experimental techniques for determining the shear strength of ceramics under large amounts of confinement (>10 GPa) are needed.
    - The strength of damaged ceramic materials is also poorly understood. The evolution of shear strength as a function of damaged material properties (composition, particle size, shape, etc.) and loading conditions is not well characterized.
    - Substantial microstructure characterization efforts are essential to relate the macroscopic behavior to actual mechanisms of failure.
  - Computational speed and memory handling have advanced so much that perhaps the modeling community should revisit more complex models

that were viewed as too complex or demanding in the past such as the NAGFRAG models (McHugh et al. 1980).

  - Attendees shared the following views on material models and codes that they felt were currently the best choice for modeling ceramics and geomaterials.

    - The EPIC code, developed by Gordon Johnson and others, along with the JHB model garnered recommendations as a good choice for modeling ceramics because of its parameterized models and particle conversion capabilities.

    - Attendees from ERDC reported favorable results using the Microplane M7 model developed by Zdeněk Bažant to model concrete (Caner and Bažant 2013).

    - The general feeling was that Lagrangian codes worked much better than Eulerian codes for modeling brittle materials.

- Polymers, composites, and biomaterials breakout meeting.

  - Several shortcomings in current soft materials modeling capabilities were brought up in this breakout discussion.

    - Improvement is required to accurately model ballistic impacts on composites. Difficulties include modeling ballistic limit velocity, delamination, back-face deformation, different geometries, and failure modes such as plug formation.

    - New characterization techniques are required that span a range of strain rates and length scales (i.e., standard techniques, including universal testing machines for quasi-static strain rates and split Hopkinson pressure bar for dynamic strain rates, may not provide information at multiple length scales needed for understanding hierarchical materials such as bone and some composites).

    - Understanding of how material architecture, design, or geometry contribute to failure behavior requires improvement.

    - Greater understanding of the material properties of soft materials such as polymers and biomaterials is required. Characterization under complex and high-strain-rate loading conditions is essential for improved modeling of dynamic failure in these materials.

    - In continuum modeling, the element size with refinement quickly approaches microstructural constituent size, which requires assigning a physical meaning to discretized elements. Continuum modeling is then ineffectual at this length scale, but multiscale modeling requires the amount of information to be reduced for the problem to be tractable. There is a need for understanding what information may be reduced at the length scale of microstructural constituents.

- Numerical technique suggestions for improvement included the following.
  - Identify canonical problems and standard types of experimental data to measure for material systems and use this to populate material models: for example, short beam shear, quasi-static indentation, depth of penetration, and V_{50} limit velocity.
- Experimental technique suggestions for improvement included the following.
  - Measure thin samples to reduce nesting effects in measurements.
  - To aid in assessing fiber rotation as a function of penetration, place leaded glass tracer yarns and use flash X-ray to measure fiber rotation adjacent to penetration. Also, the resolution of proton radiography is not sufficient to image fibers but can show density changes with shock.

5.2.4 Programmatic and Organizational Changes Needed to Support Improved Modeling and Experimental Capabilities

- There must be a serious institutional commitment to generating sufficient experimental data to parameterize existing and new material models. Often this is not the case with newer materials or material models. New models are often parameterized only for a few materials, and these material model parameters may not be distributed with the model.
  - The most widely used continuum scale material models are the Johnson-Cook models. They are widely used because they are widely available and have been parameterized for a large variety of materials. This parameterization, conducted by one of the original model developers (Johnson and Holmquist 1988), was funded by the Defense Advanced Research Projects Agency, the US DOD, the US Army, and the US Marine Corps. Given the longevity of these models, money invested in parameterization was well spent.

- Long-term efforts by the DOE to characterize the equations of state for important materials are another successful example of institutional support for materials characterization. The results of these efforts, such as equation of state tables included with DOE hydrocodes, have been leveraged by every institution who conducts continuum scale simulations that use an equation of state.

- Serious Army institutional commitment is required for developing and maintaining material models within DOE codes that are of interest to the Army. Institutions inside and outside of the Army reward developing new material models, but there is little incentive to implement them in DOE codes or support them for an extended length of time. This creates an incentive to develop models for short-term use and then discard them without making them available to the broader Army community.
    - There also needs to be an efficient mechanism for the Army to share restricted use models with the DOE code development teams. Often when DOD developed models are implemented into DOE codes, they are usually built on DOD HPC resources and are not a permanent part of DOE software repositories. When projects end or personnel move on, these models may ultimately become lost and the capability must then be redeveloped, wasting time and money already spent.
- Research-based institutions rightly prize novel experimental techniques and discoveries, but vital efforts like materials characterization—an essential component of accurate computer modeling—are often not recognized or rewarded when proven materials characterization techniques are applied to existing materials with demonstrated importance or innovative new materials.
- The DOD needs to improve funding to DOE code development teams for general support functions. The DOD HPCMP pays a substantial amount to license commercial software such as ANSYS or ABAQUS. This money supports development and technical support for commercial codes. Comparable levels of support are not provided to DOE code development teams by the DOD.
    - The DOD needs support from the DOE to build the DOE codes on the DOD HPCMP computers. These services would cost relatively little; one to 2 weeks of time per code per year is believed to be sufficient for building DOE codes on DOD HPCMP platforms. This would be a substantial improvement over the status quo.

- The DOE and the DOD would benefit from better funding of technical support for DOE software. For DOE code development teams, technical support is usually an expensive, unfunded requirement which can consume substantial resources that might otherwise go to code development. Technical support is essential for new and experienced users to draw upon to ensure timely completion of modeling efforts and should be funded accordingly.
  - One support success story is funding provided by John Rowe from Program Executive Office Ground Combat Systems (PEO GCS) and Robert Doney (ARL) for the ALEGRA hydrocode. This funding led to responsive support and high quality documentation provided to ARL users by the ALEGRA team.
- DOD institutions should consider integrating DOD personnel into DOE software development efforts allowing the DOE to leverage DOD salary investments while allowing the DOD to leverage improved working relationships and code knowledge to contribute code improvements or material models relevant to the DOD.

- The Army needs to support code and material model development that relates to its core mission space and priorities. In the view of the attendees, the Army has a spotty record of supporting code development for dynamic solid mechanics problems. The Army appears to generally accept whatever is developed by other parties. Again the exception is provided by John Rowe (PEO GCS) and Robert Doney (ARL) who have been providing support for the ALEGRA hydrocode. Various agencies have provided occasional support for the EPIC hydrocode as well. The Army does not appear to have a strong history of supporting model and simulation code development or features relevant to Army problems.

- Collaboration is often represented as desirable, but in many institutions not being the principal investigator (PI) on a project or the lead author of a paper comes at the price of being seen as playing a considerably less important and prestigious role, creating a disincentive to work collaboratively. Institutions often encourage scientists and engineers to take on many small projects as PI, leaving little time or energy for larger collaborative projects. Together, these factors can lead to fragmentation of effort and impair fruitful collaboration. Institutions should reward collaborative efforts by, for example, rewarding multi-author publications and larger, collaborative efforts.

- Material models developed under contract to the government should be considered a deliverable and they should be developed for portability. They should conform to the standards of a common portable format (such as the ABAQUS UMAT or VUMAT), follow appropriate software development practices, and be required to reproduce predefined analytical solutions as well as some experimental data for validation. Suitable analogues for portable model formats and standard problems should be available for different code types and different applications.
    - Material parameters and other material model inputs should also be considered part of the deliverable and should be maintained and/or documented, perhaps in the Defense Technical Information Center (DTIC), in such a way that Army researchers can locate and utilize them. Other agencies and organizations, such as the National Science Foundation and the National Institute of Standards and Technology, are addressing the appropriate documentation of scientific research. Collaboration with these groups and agencies to establish common practices would be helpful.

5.3 Survey Results

The survey questions are reproduced in Appendix B. A total of 17 surveys were returned to the authors each day, representing about 26% of the attendees. The survey questions and format were constructed so that responders would write free-form answers to questions about the shortcomings of the state of the art and where improvements were needed in modeling and understanding dynamic failure events. The responses were reviewed and grouped into categories based on the discussions at the ARL Dynamic Failure Forum.

The responses fell into 11 categories in order of importance:

- Constitutive Model Development and Support
- Constitutive Model Parameterization
- Experimental Development in Support of Material Behavior Exploration
- Collaboration
- Experimental Development in Support of Parameterization
- Code Improvements
- Multi-Scale Modeling
- Uncertainty Quantification

- Organizational Support
- Challenge Problem
- Modeling Post Processing Tools

An unanticipated problem with the surveys was that the responders frequently responded in incomplete sentences and occasionally their responses could be interpreted to fit in more than one category. For example, one responder indicated that “thermal effects” were one of the most important findings or recommendations of the penetration panel discussion on day one. It is not clear whether the responder meant that constitutive models should have more sophisticated treatment of thermal behavior or that more sophisticated measurements of thermal behavior need to be performed. Both are true and were discussed at some length by panelists and audience members throughout the Forum so this response was counted for both the Experimental Development in Support of Material Behavior Exploration category and the Constitutive Model Development category. Thus responses were counted in all of the appropriate categories. On average, we estimate the error in placing a response in the correct category to be plus or minus 2 responses. For topics with a small number of responses, such as comments encouraging the use of centrally organized challenge problems, the error in placing responses in the correct categories is zero.

5.3.1 Constitutive Model Development and Support

Constitutive model development garnered the most responses as is evident in Fig. 2. Great interest was shown in developing and implementing new and improved constitutive models. Twenty responses related to improving fracture models. In response to the question, “What needs to be done to advance the computational study of explosive/blast induced fracture and fragmentation events? What is the best way to do it?” one responder indicated, “Development of mesh independent numerical methods for fracture.” This was a common thread at the meeting. Another, in response to the question, “What were the most important findings of the (Computational and Theoretical Investigation of Fracture) panel?” was, “The necessity of representing to the true physical nature of damage and failure.”

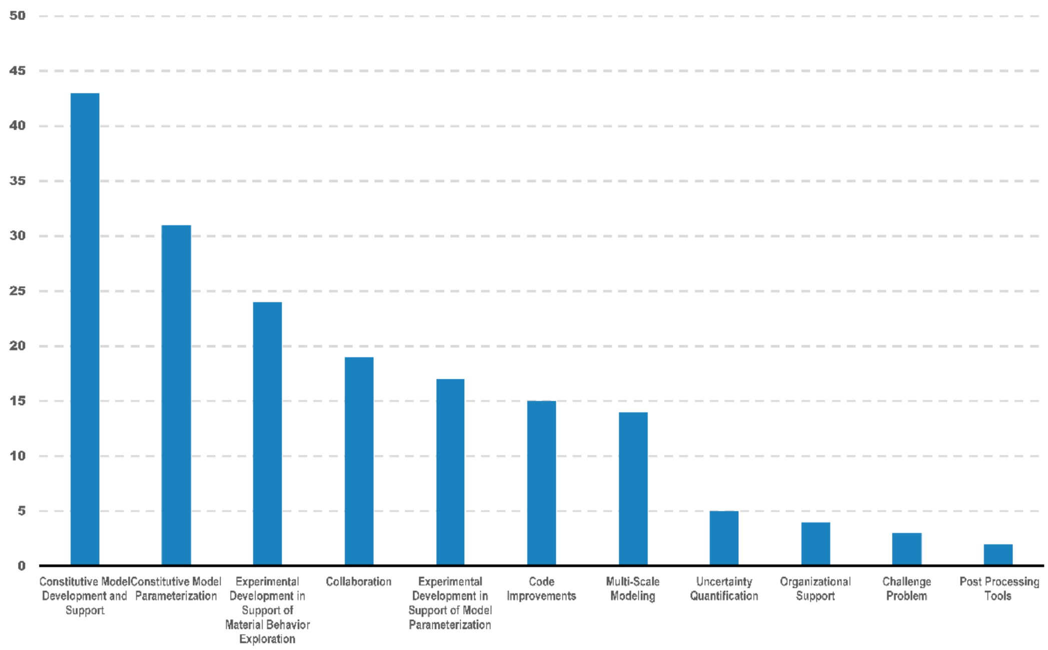

Fig. 2 Number of survey responses divided among different themes

Of the remaining responses related to constitutive model development, 8 related to the importance of using stochastic material properties or stochastic models, 5 commented on the need for material models with physically measurable parameters, 4 suggested that "better models" are needed without more specific suggestions, 2 respondents commented on model complexity with one respondent advocating greater model complexity generally and the other indicating that complex models were useful in limited cases.

Six other responses did not fit easily in any of the previous categories. These responses ranged from a general comment on the need for additional material models to a comment on the importance and difficulty of mixed zone physics.

5.3.2 Constitutive Model Parameterization

The next category in terms of response number was Material Model Parameterization with 31 responses. A large number of responses, 18, indicated that more effort should be directed toward parameterizing material models. Nine responses indicated that there needed to be more effort directed toward characterizing material variability, particularly as that related to fracture and fragmentation. Seven of these responses were provided on Day 2, the day when explosive and blast induced fracture and fragmentation was discussed. Discussion during the sessions on the 2nd day supports the importance placed on knowing material property variability to properly model fragmentation.

5.3.3 Experimental Development in Support of Material Behavior Exploration and Experimental Development in Support of Model Parameterization

Experimental Development in Support of Material Behavior Exploration was the next largest response category with 24 responses. We have chosen to group this with the 5th largest category, Experimental Development in Support of Model Parameterization, with 17 responses. The 2 categories are related and yet distinct.

Issues related to experimental improvements in support of improved understanding of material were mentioned regularly in the surveys and in the sessions. There is great interest from both experimentalists and modelers in developing a greater understanding of material behavior. Ten responses dealt with the need for improved understanding of mesoscale properties and behavior including experiments to expose and understand competing and complementary fracture mechanisms and microstructure data for mesoscale simulation. Six responses mentioned the importance of using full field diagnostics to gain additional insights into material behavior. Three responses addressed the importance of better understanding of material thermal properties.

Experimental Development in Support of Model Parameterization garnered 17 related responses. Six responses were related to the value of using full field diagnostic tools. Five responses related to fielding more time resolved diagnostic tools in general with one respondent suggesting that experiments ought to have multiple time-resolved diagnostics if possible. This was a point that was brought up during the panel discussions; multiple time-resolved diagnostics impose more constraints on inverse methods. Three responses related to coupling experimental and computational efforts, especially for inverse methods to solve explicitly for material model parameters.

5.3.4 Collaboration

The topic of improved Collaboration drew 19 responses in the surveys that were returned to us for analysis. Eleven of those responses stressed the importance of greater collaboration between modelers and experimentalists. Nine responses related to the need to improve collaboration between code users and code and/or model developers. Several responses suggested a collaborative benchmarking exercise would be useful for comparing code/model/modeler performance against the same problems across labs. Six responses suggested a need for greater collaboration between different labs, though one respondent lamented the difficulty of creating serious collaborations between labs due to bureaucratic barriers impeding transfer of funds, intellectual property, and so forth, between labs. Similar sentiments were voiced during the panel discussions.

5.3.5 Remaining Survey Response Topics

The first 5 topic areas in the surveys captured approximately 76% of responses. The remaining topic areas are important, but will be addressed in less detail. Code Improvements garnered 15 responses. Many of these responses related to the difficulty in accurately portraying material interfaces, including fractures, and the need for solver improvements for multiphysics problems. Multiscale modeling garnered 14 responses, many suggesting that multiscale modeling could provide additional insight into physical behaviors and processes that experiments currently are not capable of. Five responses related to the importance of uncertainty quantification in experiments and modeling. Four responses addressed the currently insufficient levels of institutional support for improvements in model development. One respondent commented, “We need to recognize that fracture and fragmentation are long term problems.” Substantial improvements in our understanding of and ability to study and model fracture and failure will not be addressed by short-term effort. Three respondents suggested challenge problems or competitions focused on such problems, such as the Sandia Fracture challenge, could be beneficial in improving our understanding of and ability to model fracture and failure. Two responses indicated a need for post processed tools for comparison of model data and simulation data. While this point did not generate many responses, this is nevertheless a vital point. The need to post process simulation data efficiently is becoming acute as modelers generate larger and larger volumes of data through ensembles of large simulations for uncertainty quantification activities, inverse problems, and searching through large parameter spaces for optimal designs of weapons or armor systems.

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Appendix A. Attendees

Name	Full Affiliation
Brady Aydelotte	US Army Research Laboratory
Nathan Barton	Lawrence Livermore National Laboratory
Shane Bartus	US Army Research Laboratory
John Beatty	US Army Research Laboratory
Rich Becker	US Army Research Laboratory
Todd Bjerke	US Army Research Laboratory
Curt Bronkhorst	Los Alamos National Laboratory
Matt Burkins	US Army Research Laboratory
Dan Casem	US Army Research Laboratory
Kent Danielson	US Army Engineer Research and Development Center
Stan DeFisher	US Army Armament Research, Development and Engineering Center
Bob Doney	US Army Research Laboratory
Todd Dutton	US Army Research Laboratory
Adam Enea	US Army Armament Research, Development and Engineering Center
Constantine Fountzoulas	US Army Research Laboratory
Dave Fox	US Army Research Laboratory
Denver Gallardy	US Army Research Laboratory
George Gazonas	US Army Research Laboratory
Vladimir Gold	US Army Armament Research, Development and Engineering Center
Bill Heard	US Army Engineer Research and Development Center
Dan Hornbaker	US Army Research Laboratory
Joshua Houskamp	US Army Research Laboratory
Phil Jannotti	US Army Research Laboratory
John Korbin	Sandia National Laboratory
Carl Krauthauser	US Army Research Laboratory
Mukul Kumar	Lawrence Livermore National Laboratory
Brian Leavy	US Army Research Laboratory
David Littlefield	University of Alabama at Birmingham
Jeff Lloyd	US Army Research Laboratory
Bryan Love	US Army Research Laboratory
Michael Macri	US Army Armament Research, Development and Engineering Center
Lee Magness	US Army Research Laboratory
Jim McCauley	US Army Research Laboratory
Jason McDonald	US Army Research Laboratory
Andrew Mearns	Defence Science and Technology Laboratory
Mark Merewether	Sandia National Laboratory
Chris Meyer	US Army Research Laboratory
John Niederhaus	Sandia National Laboratory

Danny O’Brien	US Army Research Laboratory
James O’Grady	US Army Research Laboratory
David Pfau	US Army Armament Research, Development and Engineering Center
John Pittari	US Army Research Laboratory
Phillip Reu	Sandia National Laboratory
Asher Rubinstein	Army Research Office
Shannon Ryan	Defence Science and Technology Organisation
Sikhanda Satapathy	US Army Research Laboratory
Steve Schraml	US Army Research Laboratory
Brian Schuster	US Army Research Laboratory
Jesse Sherburn	US Army Engineer Research and Development Center
Stewart Silling	Sandia National Laboratory
Adam Sokolow	US Army Research Laboratory
Justin Sweitzer	US Army Aviation and Missile Research, Development and Engineering Center
Pat Swoboda	US Army Research Laboratory
DeCarlos Taylor	US Army Research Laboratory
Russ Teeter	Sandia National Laboratory
Veena Tikare	Sandia National Laboratory
Andy Tonge	US Army Research Laboratory
Lionel Vargas-Gonzalez	US Army Research Laboratory
George Vunni	US Army Research Laboratory
Valerie Wagoner	US Army Research Laboratory
Tusit Weerasooriya	US Army Research Laboratory
Ray Wildman	US Army Research Laboratory
Jason Wilke	Sandia National Laboratory
Cyril Williams	US Army Research Laboratory
Mike Zellner	US Army Research Laboratory

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Appendix B. Survey Questions

ARL Dynamic Failure Forum Survey (Day 1)

Penetration Panel Discussion

1) What were the most important findings or recommendations of the panel or what were the most important issues brought up?

2) What do you feel is the next step that needs to be taken to advance the experimental study of penetration events and what is the best way to do it?

3) What do you feel needs to be done to advance the computational study of penetration events and what is the best way to do it?

4) Did you attend the **Experimental Study of Penetration** breakout discussion or the **Computational and Theoretical Investigation of Penetration** breakout discussion (Circle One)?

5) What were the most important findings or recommendations of the panel or what were the most important issues brought up at meeting you attended?

Additional Comments?

ARL Dynamic Failure Forum Survey (Day 2)

Explosive/Blast Induced Fracture and Fragmentation Panel Discussion

1) What were the most important findings or recommendations of the panel or what were the most important issues brought up?

2) What do you feel is the next step that needs to be taken to advance the experimental study of explosive/blast induced fracture events and what is the best way to do it?

3) What do you feel needs to be done to advance the computational study of explosive/blast induced fracture events and what is the best way to do it?

4) Did you attend the **Experimental Study of Fracture and Fragmentation** breakout discussion or the **Computational and Theoretical Investigation of Fracture and Fragmentation** breakout discussion?

5) What were the most important findings or recommendations of the panel or what were the most important issues brought up at meeting you attended?

6) Did you attend the Metals, Ceramics/Geomaterials, or the Composites/ Polymers/and Biomaterials breakout panel discussion?

7) What were the most important findings or recommendations of the panel or what were the most important issues brought up at meetings you attended?

Additional Comments?

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List of Symbols, Abbreviations, and Acronyms

AMRDEC	US Army Aviation and Missile Research, Development and Engineering Center
ARDEC	US Army Armament Research, Development and Engineering Center
ARL	US Army Research Laboratory
ARO	US Army Research Office
DIC	digital image correlation
DOD	US Department of Defense
DOE	US Department of Energy
DSTL	UK Defence Science and Technology Laboratory
DSTO	Australian Defence Science and Technology Organisation
DTIC	Defense Technical Information Center
ERDC	US Army Engineer Research and Development Center
HPC	high-performance computer
HPCMP	High Performance Computing Modernization Program
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
M&S	modeling and simulation
PDV	photon Doppler velocimetry
PEO GCS	Program Executive Office Ground Combat Systems
PI	principal investigator
SNL	Sandia National Laboratory
UAB	University of Alabama at Birmingham
VISAR	velocity interferometry system for any reflector

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J NEWILL
B SCHUSTER
B SORENSEN
R SUMMERS
RDRL WMM
J BEATTY
RDRL WMM B
B LOVE
RDRL WMP A
S BILYK
RDRL WMP B
T WEERASOORIYA
RDRL WMP C
R BECKER
A TONGE
J LLOYD
T BJERKE
D CASEM
J CLAYTON
B LEAVY
C WILLIAMS
RDRL WMP D
N BRUCHEY
R DONEY
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G VUNNI
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